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MACHINING OF SUPERALLOYS AND REFRACTORY METALS

DEFENSE METALS INFORMATION CENTER  
BATTELLE MEMORIAL INSTITUTE  
COLUMBUS 1, OHIO

AS 11A

## TABLE OF CONTENTS

	<u>Page</u>
INTRODUCTION . . . . .	1
MACHINING SUPERALLOYS . . . . .	3
General Information . . . . .	3
Effect of Alloy Condition on Machinability . . . . .	3
Minimizing Welding Tendencies of Superalloys . . . . .	5
Minimizing Work-Hardening Tendencies of Superalloys . . . . .	5
Turning and Facing Operations . . . . .	6
General Information . . . . .	6
Turning Setup . . . . .	6
Cutting Tools . . . . .	7
Tool Materials . . . . .	7
Tool Geometry . . . . .	8
Operating Data . . . . .	8
Milling Operations . . . . .	8
Milling Setup . . . . .	8
Cutting Tools . . . . .	13
Tool Materials . . . . .	13
Tool Geometry . . . . .	13
Operating Data . . . . .	15
Drilling Operations . . . . .	15
General Information . . . . .	15
Drilling Setup . . . . .	15
Drill Design . . . . .	17
Drill Materials . . . . .	19
Operating Data . . . . .	19
MACHINING OF REFRACTORY METALS . . . . .	19
Tungsten . . . . .	19
Effect of Surface Contamination on Machinability . . . . .	22
Turning Operations . . . . .	22
Drilling Operations . . . . .	25

TABLE OF CONTENTS  
(Continued)

	<u>Page</u>
Molybdenum . . . . .	28
General Information . . . . .	28
Effect of Anisotropy, Grain Structure, and Prior Work on Machinability . . . . .	29
General Machining Techniques . . . . .	29
Turning Operations . . . . .	30
Milling Operations . . . . .	30
Drilling Operations . . . . .	30
Tantalum and Columbium . . . . .	34
General Information . . . . .	34
Turning Operations . . . . .	34
Milling Operations . . . . .	34
BIBLIOGRAPHY . . . . .	36
Superalloys . . . . .	36
Additional Bibliography . . . . .	37
Tungsten . . . . .	38
Hot Machining . . . . .	39
Molybdenum . . . . .	39
Tantalum and Columbium . . . . .	40
APPENDIX. . . . .	A-1

# MACHINING OF SUPERALLOYS AND REFRACTORY METALS

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## INTRODUCTION

Superalloys and the refractory metals are thermally resistant materials capable of maintaining their strengths at high temperatures. This means strengths at temperatures up to 1850 F and 3500 F for the superalloys and refractory metals, respectively.

Figure 1 shows the available service-temperature ranges for these and some of the other space-age metals.

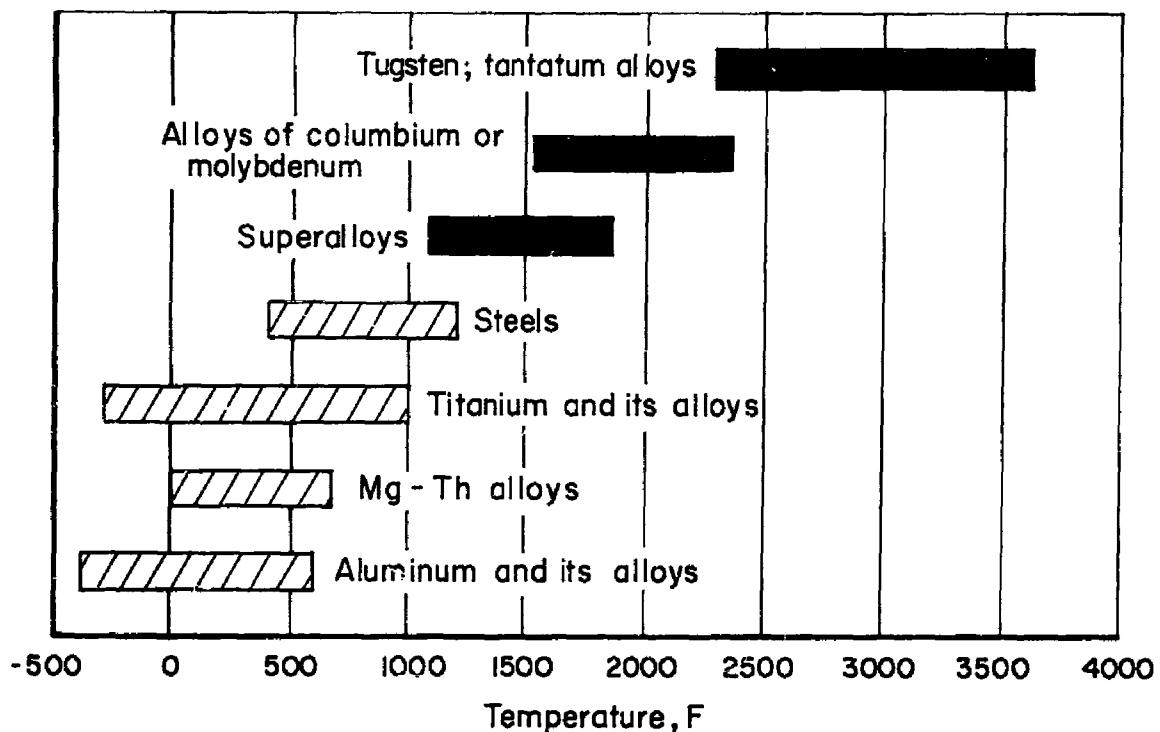


FIGURE 1. PROBABLE SERVICE TEMPERATURES FOR VARIOUS SPACE-AGE METALS

The superalloys described in this report constitute a group of complex nickel base, cobalt base, and chromium-nickel-cobalt-iron alloys. Usually, chromium, nickel, and iron are the common elements in these materials. Cobalt, molybdenum, tungsten, titanium, and aluminum also may be present in groups of two or more to form the different alloys of this group. The refractory-metals group is less complex and includes molybdenum, tungsten, columbium, and tantalum and their alloys.

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Superalloys and refractory metals are considerably more difficult to machine than ordinary constructional metals and alloys. This experience is illustrated by the machinability ratings shown in Table 1.

TABLE 1. APPROXIMATE MACHINABILITY INDEXES(a)  
OF SELECTED SPACE-AGE METALS

Metal			Brinell Hardness	Machinability Rating, per cent
Type	Designation	Condition(b)		
Low-alloy steel	AISI 4340	Spheroidized		45
Stainless steel	17-7PH	Annealed	170	45
Tool steel	H-11	Q&T	350	23
Tool steel	H-11	Q&T	515	14
Titanium alloy	Ti-6Al-4V	Annealed	312	20
Titanium alloy	Ti-6Al-4V	H.T.	365	18
Superalloy, Fe base	A-286	Aged	320	11
Superalloy, Co base	HS-25	Solution treated	200	10
Superalloy, Co base	J-1650	Aged	360	9
Superalloy, Ni base	U-500	Aged	340	6
Superalloy, Ni base	René 41	Aged	380	6
Refractory metals	Mo-0.5Ti Mo	Stress relieved Stress relieved		8

(a) Based on B1112 = 100 per cent, using carbide tools, 0.009-ipr feed, 0.10 inch depth of cut, and 0.015-inch wear land.

(b) Q&T = quenched and tempered  
H.T. = heat treated

The low machinability ratings of the superalloys generally result from the tendency of these materials to weld to the cutting edge of the tool as a built-up edge, and from the high work-hardening rates of the alloys. The built-up edge periodically spalls pulling out parts of the cutting edge with it. The work-hardened chip produced during machining is highly abrasive to the tool face, while the remaining work-hardened machined surface may notch the tool at the depth of cut line during the next cut.

Elements of the refractory-metals group exhibit individual machining problems. Molybdenum workpieces tend to chip and spall. Molybdenum also forms a built-up edge on the tool, promoting tool failure by edge spalling. Tungsten is difficult to machine because the lack of room-temperature ductility causes cracking and spalling. Columbium and tantalum can be machined without particular difficulty, provided their tendencies to gall and tear are recognized and overcome by proper techniques.

The selection of tool materials, tool design, and cutting conditions have pronounced effects on the success and cost of machining these metals. Cemented carbide and high-speed steel of maximum red hardness are usually used for cutting tools. They generally have zero to positive rakes, and just enough clearance to prevent rubbing. They must be strong, sharp, and smooth. Dull tools should be replaced when their wear lands start rubbing against the work. Additional machining requirements include rigid-tool-work setups, slow cutting speeds; positive, constant-rate feeds; and in most cases plenty of coolant, force fed to the cutting site. Heavy duty, "over-powered", vibration-free machine tools in good condition should be used. Machines that may have to run at capacity or beyond should be avoided for a smooth, chatter-free operation.

Most of these minimum requirements for superalloys and refractory metals have been described in previous DMIC literature. Information on tool materials, types of tools, machine tools needed, and general operation procedures may be found in DMIC Memoranda 30, 31, and 58.

## MACHINING SUPERALLOYS

### General Information

The superalloy group, as stated previously, includes the complex nickel-base, cobalt-base, and the chromium-nickel-cobalt-iron type alloys. Table 2 shows the compositions of some of these alloys.

### Effect of Alloy Condition on Machinability

Superalloys can be machined in the solution-treated, partially aged, or fully aged conditions. The choice depends on the strength of the alloy, the surface finish desired, and the machining operation involved.

The solution treatment dissolves normally insoluble phases in the matrix, and retains them in solution during cooling. This produces the minimum strength for the alloy. Solution-treated metal generally is gummy and shows a greater tendency to weld to the tool as a built-up edge. It also work hardens very rapidly. Since high strain hardening and a built-up edge formation can cause poor surface finish, the solution-treated condition is often rated as having a low order of machinability. Nevertheless, it is sometimes preferred for drilling, tapping, threading, and rough-machining operations.



TABLE 2. CHEMICAL COMPOSITIONS OF SOME SUPERALLOYS

Alloy	Nominal Chemical Composition, per cent											Type
	C	Co	Ni	Cr	W	V	Mo	Cb/Ta	Ti	Al	Fe	
Nimonic 90	0.10	20	51	20					2	1	5	Nickel base
Inconel 700	0.13	29	46	15			3		2.2	3.2	0.8	Ditto
Udimet 500	0.08	19.5	47	19			4		2.9	2.9	4	"
M-252 (J1500)	0.15	10	55	19			10		2.5	1.0	2	"
Hastelloy X	0.10	1.5	47	22	0.6		9				19	"
Waspalloy	0.10	18.5	51	19.5			4.25		3	1.25	2	"
René 41	0.09	11	55	19			10		3	1.5		"
Inconel X	0.08	-	70	15				1	2.5	0.70	7.0	"
Haynes Alloy No. 25	0.15	51	10	20	15							Cobalt base
J-1570	0.20	38	28	20	7				4		2	Ditto
S-816	0.38	40	20	20	4		4	4			4	"
J-1650			27	19	12				3.8			"
HS-21	0.25	62	3	27			5					"
Vitallium	0.25	64	2	28			6					"
X40; Haynes Stellite 31	0.5	55	10	25	8						1.5	"
L605			10	20	15						3	"
N-155	0.15	20	20	21	2.5		3	1			32.5	Cr-Ni-Co-Fe
S-590	0.43	20	20	20.5	4		4	4			27.5	Ditto
J-1300 (M308)	0.08		33	14	6.5		4		2	0.25	40.0	Cr-Fe-Ni

Aged alloys, although stronger than solution-treated alloys, will often machine easier because of lower work-hardening capabilities and higher yield strength-tensile strength ratios. Finer grain size and the presence of microscopic and submicroscopic precipitated metallic compounds are also thought to contribute to better machinability. The higher strengths, lower strain-hardening coefficients, and lower ductilities of aged alloys will also contribute to better surface finishes.

A few of the superalloys are not hardenable by heat treatment although they can be hardened by cold working. Consequently, these alloys are machined in the annealed condition.

#### Minimizing Welding Tendencies of Superalloys

Superalloys are reactive toward tool materials and, as such, tend to weld to the cutting tool in two locations--on the tool face and at the cutting edge. As the built-up edge sloughs off, it pulls bits of tool material from the face and from the cutting edge. This phenomenon roughens the tool face and starts a small but progressive loss of relief (wearland) on the cutting edge. Eventually, this causes the tool to rub against the machined surface. When the wear land approaches dimensions which adversely affect finish, or cause excessive rubbing and heat, the tool should be replaced.

A copious quantity of cutting fluid, properly directed, is an effective means of minimizing welding tendencies of these alloys. Some fluids, such as sulfur-base mineral oils, supply an added inhibiting action, further reducing the likelihood for these alloys to weld to tool faces and cutting edges.

#### Minimizing Work-Hardening Tendencies of Superalloys

Superalloys, in addition to their welding tendencies, are particularly vulnerable to work hardening. During the machining process, plastic deformation work hardens both the machined surface and the chip, the latter becoming quite abrasive to the tool. The amount of work hardening imparted to the work and chip is related to the cutting temperatures developed.

Cutting temperatures can be minimized by using proper tools, machining procedures, and cutting fluids. Sharp cutters with positive rake angles, adequate relief angles, and good surfaces keep cutting and frictional forces low. Slower speeds and lighter feeds than those used for stainless steel are also desirable. Furthermore, the depth of cut should be sufficient to prevent burnishing or glazing. Second cuts also should be avoided to prevent work hardening the previously machined surface.

Special mention should be made about the rubbing of tools against the workpiece. This action also contributes to excessive cutting temperatures and consequent work hardening. Rubbing can occur from any one of five conditions as follows:

- (1) Excessive wear lands
- (2) Insufficient clearance angles
- (3) An incorrectly set tool relative to the work
- (4) Feed or speed interruptions
- (5) Dwelling in the cut (without cutting).

Dwelling or riding in the cut occurs from:

- (1) Changes in tool feed
- (2) Insecurely held workpieces
- (3) Spindle float
- (4) End float
- (5) Any machine defect which tends to impede or stop the action of the cutting tool on the work.

Finally, the cooling and lubricating effects of cutting fluids will reduce cutting temperatures. Carbon dioxide impinging on the cutting site has been successful in certain machining operations. Air-oil mist coolants can be used when milling with carbides. This combination lubricates and cools without quenching the hot tool.

### Turning and Facing Operations

#### General Information

Turning and facing operations are the easiest machining operations to perform on superalloys. Nevertheless, they are classified as heavy-duty machining operations. High-quality lathes, strong auxiliary parts, and sharp cutting tools must be used. Turning operations require that tool and workpiece be mounted firmly for maximum rigidity. Slow speeds and positive feeds must be maintained throughout cutting. Copious amounts of cutting fluids must be used to lower cutting temperatures and to minimize welding to the tool.

#### Turning Setup

A rigid setup of work and tool is required for maximum tool life. The workpiece should be held firmly in the machine chuck or collet. A live tailstock center should be used whenever possible.

The tool should be held firmly in a holder which, in turn, should be firmly mounted on the machine. In this regard it is better to use a flat-base tool holder than the rocker-base type. The tool itself should be strong and set at the center line of the work. Furthermore, it should be set with a minimum of overhang to avoid tool deflection when it takes the cutting load. Machining should be done with the work as close as possible to the spindle.

The following lathe requirements are suggested for best results:

- (1) Rugged construction
- (2) Soundness of bearings and power train
- (3) Absence of backlash in feed mechanism
- (4) Snug, clean, and correctly lubricated machine slides
- (5) Ample spindle power to maintain cutting speed throughout cutting
- (6) Freedom from vibration.

#### Cutting Tools

Cutting tools used for turning superalloys include high-speed steel tools, brazed carbide tools, or solid carbide inserts clamped in mechanical tool holders. High-speed steel tools are available in a variety of sizes and shapes as indicated in tool producers' catalogs. The same is true for brazed carbide tools. Mechanical tool holders of various styles are also available.

Since sharp tools are required, the tool itself should not be allowed to wear beyond an 0.015-inch wear land. Larger wear lands cause higher cutting temperatures and produce excessive residual stresses in the work-piece.

#### Tool Materials

High-speed steel, nonferrous cast alloys, and carbide tools can be used to machine superalloys. Cobalt grades of high-speed steel usually perform best, although high-vanadium high-speed steel (and slower cutting speeds) should be used for intermittent cuts. The harder alloys machine best when the harder cemented-carbide tools, such as C-2, C-3, or C-4, are used.

### Tool Geometry

Recommendations for tool angles can be summarized as follows:

- (1) Positive rake angles
- (2) Higher than normal relief angles
- (3) A small end cutting edge angle
- (4) A large side cutting edge angle
- (5) A sharp corner or nose.

A balanced rake-relief angle combination should be selected to produce a tool capable of withstanding the cutting forces involved. Table 3 shows a representative group of tool geometries which can be used when machining superalloys.

### Operating Data

Conditions recommended for turning superalloys are given in Table 4. Cutting speeds faster than those shown are sometimes used to obtain reasonable production rates at the expense of tool life. Lower cutting speeds are used for turning scaled workpieces.

Positive feeds must be used. The tool should never ride on the machined surface without cutting. Feeds below 0.0035 ipr tend to burnish the work surface.

When a finishing cut is made, the final cut should be deep enough that machining will occur below the work hardened surface left by the roughing operation.

A heavy flow of coolant should flood the cutting zone throughout machining.

### Milling Operations

#### Milling Setup

The precautions described for turning also apply in the more difficult operation of milling superalloys. Climb milling is preferred in order to obtain a shorter tooth path in these difficult materials. It also promotes a thin chip as the cutter leaves the work.

TABLE 3. TOOL MATERIAL AND GEOMETRY

Tool Material (b)	Geometry	Tool Angles, degrees (a)						Nose Radius, inch	Chip Breaker
		Rake (c)		Relief (d)		Cutting Edge (e)			
		Back	Side	Side	End	Side	End		
Cobalt types of high-speed steels	A	8-12	6-8	5-8	7-10	10-15	10-15	-	-
Ditto	B	7-10	5-8	5-8	7-10	10-15	10-15	-	-
"	C	5-8	5-8	5-8	7-9	10-15	8-15	-	Yes
"	D	7-10	5-8	7-10	7-10	10-15	8-15	-	-
"	E	0	15	4-5	4-5	0	5	1/32	-
"	F	0-8	8-15	4-5	4-5	15-25	10-20	1/32	-
"	G	5-10	5-10	5-8	7-10	10-15	10-15	-	Yes
"	H	7-10	5-10	5-8	7-10	10-15	10-15	-	Yes
"	I	4-6	4-6	4-6	4-6	-	-	-	-
"	J	4-6	15-20	4-8	3-5	8-12	8-12	(c)	-
Castalloy	F	0-8	8-15	4-5	4-5	15-25	10-20	1/32	-
Ditto	K	5-10	5-8	5-8	7-10	10-15	8-15	-	-
Carbide grades C-1 to C-8, inclusive	L	0-3	6	6	6	0	6	0.02	-
Ditto	M	0-3	6	7	7	45	-	-	-
"	N	0-8	8-15	4-5	4-5	15-25	10-20	<1/32	Yes
"	O	5-8	8-10	5-7	5-7	15-30	-	1/32	-
"	P	15	10-15	6	6	-	-	-	-
"	Q	-6	9	6	6	30	9	-	-
"	R	+2	6	6	6	8-12	8-12	1/32	-
"	S	8-12	4-7	3-6	3-6	6-10	4-8	1/32	-
"	T	0	0	7	7	15	15	1/32	-
"	U	+5	NA	7	7	45	45	1/32	-
"	V	0	7-10	7-10	7-10	45	5	1/32	-

(a) See Figure 4-2

(a) See Figure A-3.

(b) See Tables A-1 and A-3.

(c) Positive rake angles reduce cutting forces and cutting temperatures. Negative rakes normally do not work so well. However, they can be used on some alloys if a chip curler is ground in. Two or three curls of the emerging chip is best.

(d) The higher than normal relief angles will permit more wearing time for any given wear land.

(e) The larger side-cutting edge angles distribute the chip load over a longer cutting edge of the tool. This results in smaller cutting forces (and lower cutting temperatures) and a greater area for heat absorption by the tool. A small end-cutting edge angle promotes good finish by supplying an increased point angle. It also produces a stronger tool point without resorting to a large nose radius.

(f) A large nose radius is not desirable because of possible chip crowding. The chip should flow smoothly and evenly during the machining operation.

TABLE 4. TURNING SUPERALLOYS

Machining Operation										
Alloy Designation	Alloy Condition	Tool Material(a)	Design (b)	Roughing			Finishing			
				Speed, fpm(c)	Feed, ipr	Depth of Cut, inch	Speed, fpm(c)	Feed, ipr	Depth of Cut, inch	
René 41	Aged	M <sub>3</sub> , HSS	?	---	---	---	20	.002-.006	.01-.05	Chemically active soluble oils
		Carbide C-2	L, M, N, O	35-60	.01-.015	.05-.125	---	---	---	
Hastelloy X	Solution treated	Carbide C-3	U, V	---	---	---	60-120	.004-.010	.015-.15	Sulfur-base oil
		HSS	C	18-21	.007-.011	.025-.045	18-21	.003-.008	.008-.011	
Waspalloy	Aged	Carbide	O	68-88	.008-.016	.05-.10	68-88	.006-.009	.011-.015	Chemically active soluble oils, sulfur-base oils, or sulfur-base oils w/10-25% kerosene
		HSS	F	10-20	.015	.09	---	---	---	
	CA	F	40	.015-.025	To .25	---	---	---		
	Carbide	N	40-75	.008-.018	.045-.18	75-125	.005-.010	.015-.045		
Solution treated		HSS	F	25-35	.015	.09	---	---	---	Heavy sulfur-base or sulfochlorinated oils
		Carbide	N	35-50	.010-.015	.015-.125	60-90	.005-.010	.015-.045	
Inconel X	Aged	Carbide	N	20-35	.015	.093 max	---	---	---	Soluble oil and lubricant
		HSS	F	40	.015-.025	.25 max	---	---	---	
	CA	M, N, O	30-45	.008-.013	<.093	---	---	---		
	Solution treated	HSS	E, F	10-20	.01-.015	.093 max	---	---	---	
		Carbide	N	60	.008-.018	.187 max	60-90	.005-.010	.015-.045	
		Carbide	N	40-75	.010-.015	.05-.125	30-60	.003-.008	.03	
Havlys alloy No. 25	Aged	Carbide	M, N, O	70-80	.010-.015	.015-.045	75-125	.003-.010	.015-.045	Soluble oils or sulfur-base oils
		HSS	E	25	.009	.062	---	---	---	
	Solution treated	Carbide	N or O	30-45	.010-.015	.060-.10	45-55	.006-.010	.008-.010	
		Carbide C-6	N	100	.009	.10	30-45	.003-.005	.008-.010	
J-1570	Aged	Carbide	M, N, O	40-75	.010-.015	.063-.125	55-100	.004-.009	.031	Sulfur or sulfochlorinated oil
S-816(g)	Aged	HSS	C	10-15	.008-.009	.25	---	---	---	
		Carbide	M, N, O	25-35	.009-.012	.25	---	---	---	
	Alloy X-40	Carbide	L	30-60	.005-.008	.015-.05	---	---	---	
		Carbide	N	45-65	.010-.015	.05-.125	60-80	.005-.008	.015-.05	
HS-21	Cast	Carbide	M, N, O	10-40	.009-.012	.25	65	.005-.008	.005	General-purpose cutting oil and kerosene
L-605	Annealed	Carbide	T	150	.008	.06	---	---	---	

TABLE 4. (Continued)

Alloy Designation	Alloy Condition	Tool Material(a)	Design(b)	Machining Operation						Cutting Fluid
				Roughing			Finishing			
				Speed, fpm(c)	Feed, ipr	Depth of Cut, inch	Speed, fpm(c)	Feed, ipr	Depth of Cut, inch	
J-1650	Solution treated	Carbide	N	30-50	.015-.020	.09-.25	—	—	—	Sulfur-base oils
	Aged	Carbide	N	40-75	.010-.015	.05-.125	75-100	.005-.01	.015-.05	Sulfur-base oils
J-1700		Carbide C-5a	M, N	60-80	.015-.020	.09-.25	100-125	.005-.01	.015-.045	Soluble oils or sulfur-base oils
		Carbide C-7a	M, N	80-100	.010-.015	.05-.125				
N-155 S-550	Aged	HSS	C	18-20	.007-.011	.025-.045	18-20	.003-.008	.008-.011	Sulfochlorinated oils
		CA	K	20-40	.007-.011	.025-.045	20-40	.003-.008	.008-.011	
		Carbide	O	50-72	.008-.013	.050-.10	68-90	.006-.009	.011-.015	

(a) HSS = high-speed steel; CA = cast alloy.  
(b) See Table 2 for details.

(a) HSS = high-speed steel; CA = cast alloy.

(b) See Table 3 for design data appropriate to the code shown.

(c) See Table A-4 for conversion of fpm to rpm.

(d) Machines best in all conditions.

(e) Machines best in solution-treated condition.

(f) Machines best in partially aged condition.

(g) Machines best in the aged condition.



Work-holding fixtures should hold and support the workpiece as close to the machine table as possible. The solid part of the fixture (rather than the clamps) should absorb the cutting forces.

Plain or slab milling cutters should be mounted so that the cutting forces will be absorbed by the spindle of the machine. This can be accomplished by using cutters with a left-hand helix mounted for a right-hand cut, and vice versa. When two milling cutters are used end-to-end on the arbor, cutters having helixes of opposite hand to the cut involved should be used. This setup neutralizes the cutting forces which tend to push the cutters away from the arbor. When using arbor-mounted cutters, the arbor should be of the largest possible diameter. In addition, the arbor should be supported on both sides of the cutter with overarm supports.

Face mills are generally used in preference to plain milling cutters or slab mills for milling plane surfaces. Face mills are more efficient in removing metal and produce more accurate surfaces than plain milling cutters do. Because of their more rugged nature, face mills permit the use of faster feed rates. In addition, the complicated supports and bracing usually required for arbor-mounted cutters are unnecessary when face mills are employed.

End mills are used for light operations such as profiling, facing narrow surfaces, and slotting. Because of an inherent lack of rigidity, end mills should be as short as possible, and their shank diameters should equal the cutting diameter. Hence, special end mills may be necessary for adequate tool life. A standard end mill having a shank diameter smaller than the cutting diameter may give poor tool life because of excessive cutter deflection.

When the end of the cutter will be doing the cutting, the hand of the helix and the hand of the cut should be the same, i.e., right-hand helix for a right-hand cut. When the periphery of the cutter is used, the opposite is true, i.e., a left-hand helix for a right-hand cut.

The following machine tool requirements are suggested to give the best results:

- (1) Rugged construction
- (2) Sturdy spindle bearings in good condition for heavy cutting loads
- (3) Flywheel assistance
- (4) No backlash in feed mechanism
- (5) Snug, clean, correctly lubricated gibs and slides
- (6) Adequate power to maintain cutting speed
- (7) Freedom from vibration.

## Cutting Tools

The milling of superalloys requires cutters with adequate body and tooth sections to carry the cutting load imposed by the particular operation. Special designs of milling cutters may be needed, rather than those generally available in commercial stock sizes. Cutters should have helical teeth where possible to promote smooth cutting action. They should also have as many cutting edges or teeth as practical without sacrificing necessary chip space. This will partly offset the relatively low speeds at which cutters must operate in these materials.

Sharp cutting tools must be used, and they should be ground as frequently as required. Cutters should be ground to run as true as possible. All teeth should cut the same amount of material. It is advantageous to have at least two cutters for a given operation. Experience indicates that minimum machine downtime occurs when the entire cutter is replaced by the standby.

## Tool Materials

Both high-speed steel and insert-type carbide cutters can be used to mill superalloys. High-speed steel cutters are more reliable in terms of eliminating sudden failure. In addition, high-speed milling cutters give better short-time cutting speed but fall off in tool life faster than carbides do. For René 41, the crossover point is around 35 fpm and 25 minutes tool life. Hence, for general-purpose use and on small-lot production, high-speed steel cutters are preferred to carbide cutters. Types M-3 and T-15 high-speed steel have been used successfully for specific milling applications. An axial hole should be a part of the high-speed-steel cutter design to allow coolant injection at the site of cutting.

Carbide insert-type cutters can successfully mill superalloys when reasonable care is exercised. Carbide grades C-1, C-2, C-5a, and C-7a have been used for various rough- and finish-machining operations.

## Tool Geometry

An axial rake is usually recommended to reduce impact against the cutter and to provide a suitable shearing action. A large radial rake angle helps to reduce the cutting load, work hardening, and cutting temperature. The size of this angle will be limited by the strength of the tooth. Relief angles, although larger than standard, should be kept as low as possible--just enough to prevent the tool from dragging on the workpiece. When practical, a bevel angle should be used to protect the chamfer as the tool enters the cut.

A group of tool geometries which have been used is shown in Table 5.

TABLE 5. TOOL GEOMETRIES SUITABLE FOR MILLING SUPERALLOYS

Tool Materials(b)	Geometry	Tool Angles, degrees(a)							Chamfer, degrees
		Rake		Relief		Cutting Edge			
		Axial	Radial	Face	Peripheral	Peripheral	Face		
High-speed steel	FMA	0	10	5(c)	5(c)	45	5	0	
Ditto	FMA <sub>1</sub>	15	10	2-4(c)	2-4(c)	0	1-3(c)	45	
"	FMB	10-15	10-15	3-5(c)	3-5(c)	0	5-7	45 with 22-1/2 bevel	
"	FMB <sub>1</sub>	+10	+10	5	5(c)	45	5	0	
"	PMC	10-12(e)			6(c)				
"	PMD	10-12(e)			4-5(d)				
"	EME	35			12-15	45x0.030 in.			
"	EME <sub>1</sub>	30	7		6			N.R. 0.060	
"	SMF	10	10	10	10	45	5	N.R. 0.060	
"	SMF <sub>1</sub>	10	10	6	6				
"	G	+5	+5	6	6	15	8		
"	H	0	+5	6	6	15	8		
Carbide	FMI	+15	-10	5	5	0	5	0	
Ditto	FMJ	-5	-5	5	5	15	6		
"	FMK	0	0	7	7	15	15	N.R. 0.032R	

(a) See Figure A-1.

(b) See Tables A-1 and A-3.

(c) Add 5 degrees for secondary clearance values.

(d) Add 3 degrees for secondary clearance values.

(e) Where cutting edge is a helix (slab mill, end mill, etc.) axial rake = helix angle.

Note: The following cutter codes are used: FM = face mill; PM = peripheral mill; EM = end mill and SM = side mill.

### Operating Data

Conditions recommended for milling the superalloys are given in Table 6. Cutting speed is the most critical factor; excessive speeds cause overheating of the cutting edges and subsequent rapid tool failure. When starting a new job, a cutting speed in the lower part of the recommended range should be used.

Lower feed values will minimize deflection in the workpiece if this is a problem. It is best to maintain a uniform feed. Cutters should not idle in the cut, since the surface will work harden and cause rapid tool failure.

Whenever the cut or the machine tool permits, a climb cut (down milling) should be used. This should not be attempted, however, unless all lost motion is removed from the milling-machine-table feed mechanism.

### Drilling Operations

#### General Information

Drilling is the most difficult machining operation to perform on superalloys. In the first place, the thrust and torque forces are higher than those needed for drilling conventional materials. The center web of the drill does not cut but extrudes the metal in its vicinity. Consequently, the bottom of the hole can work harden sufficiently to cause early drill failure. Work hardening can be minimized by using drills with thinner webs. A constant, positive feed is necessary, and the drill must be kept sharp.

#### Drilling Setup

Successful drilling requires heavy-duty machine tools with plenty of power, adequate rigidity, and a true running spindle with no end play. Parts must be properly supported at the point of thrust by fixturing. In some cases, this can be accomplished by casting a low melting-point matrix around the part.

Drill rigidity is also important. Drills should be as short as possible. For deep-hole drilling, several lengths of short drills may be employed in sequence. A drill bushing, if possible, should be incorporated in the setup for additional rigidity.

Proper alignment of the supported work and drill is also necessary to prevent premature drill breakage.

TABLE 6. MILLING SUPERALLOYS

Alloy	Condition	Tool Material (a)	Design (b)	Milling Operation						Cutting Fluid
				Roughing			Finishing			
				Speed, fpm (c)	Feed, ipt	Depth of Cut, inch	Speed, fpm (c)	Feed, ipt	Depth of Cut, inch	
René 41	Aged	HSS (M-3)	FMA, FMB EME	-- --	-- --	-- --	15-20 15-20	.002-.006 .002-.004	.010-.015 .010-.015	Sulfur-base oils
Hastelloy X	Solution treated	HSS	--	15-25	.002-.006	.10-.20	--	--	--	Sulfur-base oils
Waspalloy X-25	Solution treated	Carbide C-1	FMI	40-60	.006-.010	.125-.25	--	--	--	Sulfur-base or chemically active soluble oil
J-1500	Aged	Carbide C-2	FMI	--	--	--	60-100	.003-.006	.03-.125	Chemically active soluble oils, sulfur-base oils, or sulfur-base oils with 10-25% kerosene
Udimet 500		HSS (T-15)	EME	30	.002	.25	--	--	--	
René 41(a)		HSS (T-15)	SMF	20	.010	.06	--	--	--	
		Carbide	FNJ	--	--	--	50	.002	--	
Inconel X and Nimonic 90	Solution treated	HSS	FMA, FMB EM SM	-- -- --	-- -- --	-- -- --	25-35 25-35 25-35	.003-.006 .001-.003 .002-.004	-- -- --	Sulfurized-chlorinated oils sometimes thinned with 10-25% kerosene
	Aged	HSS	FMA, FMB EM SM	-- -- --	-- -- --	-- -- --	15-30 15-30 15-30	.003-.006 .001-.003 .002-.004	-- -- --	
	Solution treated	Carbide C-1	FMI	40-70	.006-.010	.125-.25	--	--	--	
Haynes Alloy No. 25	Aged	Carbide C-2	FMI	--	--	--	40-90	.003-.006	.03-.125	Sulfurized-chlorinated oil or chemically active soluble oil
	Solution treated	HSS	--	15-17	.002-.006	.10-.20	--	--	--	
		HSS (T-15)	EME FMA	30 35	.001 .005	.25 .060	-- --	-- --	-- --	
J-1570 S-616 J-1650(e)	Aged	Carbide C-1 Carbide C-2	FMI	40-60 --	.006-.010 --	.125-.25 --	-- 60-100(e)	.003-.006 --	.03-.125 --	Kerosene and sulfurized oil
L-6-5	Annealed	Carbide C-1 HSS (T-15) HSS (M-2)	FMK EME SMF	50 22 28	.003-.01 .0056 .0054	.06-.08 .060 .060	-- -- --	-- -- --	-- -- --	
HS-21	Cast	Carbide C-2	--	--	--	--	100	.0011	--	(f)
J-1300 M-138	--	Carbide C-5a Carbide C-7a	FMI FMI	50-75 --	.0060-.010 --	.125-.250 --	-- 70-110	-- .003-.006	-- .03-.125	Waterbase soluble oil or sulfur-base oil
N-155 S-590	Aged	HSS	--	15-25	.002-.006	.10-.20	--	--	--	Sulfur-chlorinated oil

- (a) HSS = high-speed steel.  
 (b) See Table 5 for design data appropriate to the code shown.  
 (c) See Table 4 for conversion of fpm to rpm.  
 (d) Aged only.  
 (e) Use 40-75 fpm for J-1650.  
 (f) Try the various cutting fluids listed in this table.

## Drill Design

Drills should be of the heavy-duty type with heavy webs and polished flutes. The choice of helix angles will depend on the job conditions, and on the alloy being drilled. Both low- and high-helix-angle drills are used. Generally the drill life increases as the included or point angle increases from 90 to 140 degrees. The flatter-point angles provide maximum support in the critical area of the chisel edge which can become damaged due to the high axial loading on the drill.

Excellent results have been obtained with special drills possessing internal axial cooling holes through which coolant can be pumped under high pressure to the cutting site. This arrangement not only cools, lubricates, and minimizes welding but also helps in chip removal. Cutting speeds used for these drills approach the cutting speeds used in turning.

Pilot drills should not be used. The cylindrical wall work hardens to some degree with any drilling operation and the drill which subsequently opens the hole may fail very rapidly.

It is essential that drills are kept sharp. In fact, it may be necessary to resharpen the drill at least once or twice during the operation. If a drill fails before the hole is completed, the material may have become so work hardened that it seems impossible to finish the hole. Some success in getting past the work-hardened area has been achieved by using a drill with the lips flattened to zero rake. This drill should be of the same diameter as the broken drill but should utilize a different included angle. This drill can be hand fed slowly through the work-hardened layer, after which the drill is removed and saved for the next emergency.

Drill geometry is important in the successful drilling of superalloys. Both low and high helix type drills have been used. The point angles involved may vary from 118 degrees to 140 degrees. Drills with 118 degree point angles usually use a high drill-clearance angle. The flatter point angles (from 130-140) can be used with clearance angles running moderately low. Occasionally points are chamfered (with a smaller angle chamfer than the drill point) to protect the cutting corner.

A crankshaft point is needed to reduce the area of contact and thereby minimize work hardening caused by the extrusion action of a conventional chisel point.

Drill geometry can be a sensitive factor. Two drills of apparently the same grind can yield substantially different tool lives--either because of minute differences in geometry or because of excess heat produced in grinding.

Table 7 lists some of the designs which have been used when drilling superalloys.

TABLE 7. DRILL MATERIAL AND GEOMETRY FOR DRILLING SUPERALLOYS

Drill Material(b)	Geometry	Drill Angles(a), degrees			Web	Point	Flutes
		Rake Helix	Relief Clearance	Cutting Edge Point Angle/2			
High-speed steel	DA	28	10-15	59-67.5		Crankshaft	Polished
Ditto	DB	28	10	67.5-70	Thin 1/3		
"	DC		10	59		Split	
"	DD		10-12	59		Crankshaft	
"	DE	12	9	67.5		Conventional	
"	DF		12-15				
"	DG		6-12	65-70	Thin 1/2		
"	DH(c)		10-12	59		Crankshaft	
"	DI(d)		10-12	67.5		Crankshaft	
"	DJ	12		67.5	0.008 inch	Split	
"	DK	33					
Carbide C-1	DL			59		Notched	

- (a) See Figure A-2.  
(b) See Tables A-1 and A-3.  
(c) For deep holes.  
(d) For sheet.

## Drill Materials

High-speed steel drills are usually used for drilling superalloys. The types used include M-2, M-33, and M-36. The cobalt grades generally perform better than the standard grades of high-speed steels.

Carbide drills can be useful on specific jobs. However, their high cost coupled with the high incidence of breakage usually prohibits their use. Only small amounts of lip and corner wear are permissible with carbide drills.

## Operating Data

Proper drilling technique, along with high drill rigidity, is an effective means of achieving good tool life.

The high-strength superalloys often require spindle speeds lower than are available on conventional drill presses. Optimum speeds depend on the depth of the hole and on the feed rate. Speeds must be reduced for deep holes to compensate for the difficulty of getting the cutting fluid to the cutting area. Speeds should be reduced if the feed is increased. In the case of larger drills capable of withstanding high torque and thrust forces, the combination of slow speed and heavy feed will often increase production.

In every case, a constant, positive feed is essential. The drill must not dwell in the hole without cutting. Therefore, off-hand drilling is not recommended. The drill should be pulled out of the hole frequently to free it from chips, and to permit intermittent cooling of the drill.

Ordinarily, mineral oils with 2.5 per cent active sulfur are superior to water-base cutting fluids. When drilling deep holes, a soluble oil coolant or a chemically active soluble oil coolant may be put into the hole under pressure. The low heat conductivities of the superalloys necessitate the use of large quantities of coolant.

Table 8 contains some operating data which can be used when superalloys are to be drilled.

## MACHINING OF REFRACTORY METALS

### Tungsten

The production of tungsten ingots is based primarily on the powder-metallurgy process. Sintered-tungsten ingots, however, must be given a preliminary cold working operation, such as swaging, in order to make them amenable to fabrication processes such as rolling, drawing, or spinning.



TABLE 8. DRILLING SUPERALLOYS

Alloy Designation	Condition	Size Drill, inch	Tool Material	Feed, ipr	Speed, fpm	Geometry	Cutting Fluids
René 41	Aged		Co-HSS M-33 - HSS Carbide tipped	0.002-0.006 0.001 0.002-0.006	4-8 10 10-20	DA DJ DA	Sulfur-base oils or sulfo- chlorinated oils
Hastelloy X	Solution treated		Co-HSS Co-HSS	0.003-0.007	14-21	DB	Sulfur-base oils
Waspalloy	Solution treated	1/8-1/2 1/8-1/2	Co-HSS Carbide tipped	0.002-0.006 0.002-0.006	8-12 20-35	DA DA	
Inconel X	Solution treated	1/16-1/4 1/4-3/4 3/4-2 1/8-1/2	Co-HSS Co-HSS Co-HSS Carbide tipped	0.0005-0.002 0.002-0.004 0.004-0.006 0.002-0.006	10-20 10-15 25-40	DG DA	Sulfurized- chlorinated with or without kerosene
	Aged	1/8-1/2	Co-HSS	0.002-0.006	7-12	DA	
J-1500	Solution treated	1/8-1/2	Carbide	0.002-0.006	20-50		
Nimonic 90		0.63-0.25 0.25-0.75	Co-HSS-M33 Co-HSS	0.005-0.002 0.002-0.004	10-20	DA	
Udimet 50C		0.75-2	Co-HSS	0.004-0.006			
M-252							
Haynes Alloy No. 25	Aged	1/8-1/2 1/4	Co-HSS HSS - M-3 Carbide tipped	0.002-0.006 0.005 0.001-0.003	7-12 30 12-20	DA DA DB	
J-1650	Solution treated						
	Aged		T4-HSS M-35 - HSS Carbide C-1	0.002-0.006 0.002-0.006	8-12 20-35	DA	
J-1570							
S-316	Aged	1/8-1/2 1/8-1/2	HSS Carbide C-1	0.002-0.006 0.002-0.006	10-15 25-40	DA DA	

TABLE 8. DRILLING SUPERALLOYS (CONTINUED)

Alloy Designation	Condition	Size Drill, inch	Tool Material	Feed, ipr	Speed, fpm	Geometry	Cutting Fluids
Haynes Alloy No. 31 Alloy X-40	Aged		Carbide tipped	0.001-0.003 0.0005	12-18 50	DL	
Haynes Stellite Alloy No. 21	Cast		Carbide tipped	0.001-0.003 0.0005	12-18 100	DL	
L605	Annealed		HSS HSS ~ M33	0.003 0.002	4 30	DC DC	Sulfurized oil with or without kerosene (1:1)
N-155	Aged	0.75-2.0	HSS	0.003-0.007 (rough)	14-20	DB	Soluble oil or sulfur-base oils
S-590		0.25-0.75	HSS	0.002-0.004 (finish)			
J-1300 (no cobalt)		1/8-1/2 1/8-1/2	HSS Carbide	0.002-0.006 0.002-0.006	8-12 20-35	DA	Soluble oil or sulfur-base oils

All forms of tungsten are difficult to machine. Furthermore, no two pieces of tungsten seem to machine alike. The lack of room-temperature ductility results in cracking and spalling of the workpiece during machining.

This brittleness, however, can be alleviated by heating tungsten to above the brittle-to-ductile transition temperature of the part\*. Table 9 shows how a rise in workpiece temperature reduces the strength and increases the ductility of annealed tungsten. Correspondingly, tungsten has been successfully machined by hot-machining techniques.

TABLE 9. EFFECT OF TEMPERATURE ON TENSILE PROPERTIES OF ANNEALED TUNGSTEN

Temperature, C	Yield Strength, psi	Tensile Strength, psi	Elongation, per cent	Reduction in Area, per cent
26	--	91	0	0
100	--	96	0	0
200	61.5	72	1.6	2.3
300	28.3	82	24	22
400	12.6	56	45	57

#### Effect of Surface Contamination on Machinability

If tungsten powder is hot pressed in a graphite die, the surface of the resulting part can become contaminated with a very hard tungsten carbide skin. This skin is difficult to cut and should be removed. Barrho(2)\*\* reports that skins from 1/16 to 1/8 inch thick may be removed by selective oxidation at 1750 F. Skins less than 1/16 inch thick can be removed by machining with negative-rake tools.

#### Turning Operations

General Information. Wrought and sintered tungsten present similar machining problems. Wrought tungsten, however, may require somewhat lower feeds and depths of cut because of its higher strength levels. Very low

\*Wrought tungsten parts: 356 F; recrystallized tungsten: 625 F.

\*\*See Bibliography on page 38.

machining speeds tend to produce fine pulverized cold chips or powders. "Chatter", which may result from such conditions, leads to premature tool failure by edge chipping. Higher speeds produce a dark red-hot continuous chip and are more desirable. High chip temperatures, however, should be avoided to prevent chips from welding to the tip of the cutting tool. This phenomenon will also cause premature tool failure by chipping.

When red-hot chips are generated, the chip formation from wrought tungsten should be somewhat smoother than that produced from sintered tungsten. Consequently, machined surfaces of wrought tungsten should be somewhat better than those of sintered material. Because of the tendency of tungsten to chip and crumble, especially on terminal surfaces, all cuts except light finishing cuts should be made working toward the center.

Turning Set-Up. As in the case of superalloys a rigid set up of work and tool is required for maximum tool life. The workpiece should be held firmly in the machine. A worn collet sleeve, or one having insufficient longitudinal draw movement, will not grip the work adequately. Clamping shims should be placed at strategic areas to prevent crushing of any edges. Clamping pressures should be uniformly applied.

The tool should be strong and held firmly in its holder. It should be set with an overhang not exceeding the length of the tip. Mechanical tool holders should be set with only enough overhang to allow access to the clamping screw.

Modern lathes should be used for turning tungsten. They possess the necessary characteristics of firmness, dynamic balance of rotating elements, and improved bearings for greater cutting loads and speeds. Lathe requirements are summarized on page 7.

Cutting Tools. Brazed tools have been used for boring tungsten parts. They may be purchased in standard sizes and styles, or they can be made up in the shop. In either case a carbide insert is brazed into a suitably recessed shank. Carbide inserts also can be clamped to a recessed tool holder. Clamping avoids brazing strains which sometimes are induced in the carbide inserts.

Throwaway carbide inserts set in negative rake mechanical tool holders also can be used for single-point turning. Throwaway inserts are preground; these are thin carbide inserts which are clamped between a bottom carbide shim and a top chip breaker.

The tools described above are available in a wide range of styles and sizes. Additional information and data on these tools may be found in manufacturers' brochures or catalogues.

Sharp-cutting tools must be used at the start of a turning operation. Tools should not wear beyond a predetermined wear land since this can cause excessive cutting pressure and poor surface finish. Tool surfaces over which chips pass should be lapped or honed to a high finish, with the direction of finish corresponding to the intended chip flow direction. A rough chip-bearing surface can cause a properly designed tool to deteriorate rapidly.

The proper utilization of tools depends on the skill used in applying them to the machine and to the job and to the care they receive in the shop. Grinding practice is particularly important. In addition, conscientious inspection of tools during machining will help to preserve tools and to minimize scrap. It is impossible to emphasize too strongly the importance of tool preparation and care. The time spent will be amply repaid.

Tool Materials. Turning operations are best accomplished with carbide tools, and Grade C-2 carbide usually gives the best results.

When selecting carbides made by different manufacturers, it should be remembered that the so-called equivalent grades are not necessarily standardized. Some differences even occur among lots of the same grade made by the same manufacturer. Easier-to-machine materials permit so-called equivalent tools to be interchanged at will without a noticeable change in tool performance. With more difficult-to-machine materials, however, the slight variations between "equivalent" grades can become significant.

Tool Geometry. The tool geometries listed in Table 10 have been used for tools when machining tungsten.

TABLE 10. TOOL MATERIALS AND GEOMETRY

Operation	Descaling	Turning						Boring
Workpiece Temp.	Room	Room Temperature					Hot (800 F)	Room
Tool Geometry	A	B	C	D	E	F	G	
Back Rake, degrees	-5	-5	-5	-5	-5	+8	0	+12
Side Rake, degrees	-5	-5	-5	-5	-5	*	5 to 10	6
End Relief, degrees	*	5	5	5	5	*	3	7
Side Relief, degrees	*	5	5	5	5	*	3	7
ECEA, degrees	*	3	0	5	50	*	3 to 5	38
SCEA, degrees	45	0	0	45	45	30	5 to 45	40
Nose Radius, inch	*	3/64					0.01	
Appropriate tool- holder style	+SETN	+TGTR	+TFTR	45GRT	TETR+			TSD (Brazed)
Carbide Grade	C-2	C-2	C-2	C-2	C-2	C-2		C-2

\*No data.

Operating Data. Recommended turning data for tungsten are given in Table 11. When turning tungsten, feeds should not overload the cutters and equipment. A uniform, positive feed should be maintained during cutting. Tools should not ride on the work without cutting since the surface may become glazed. Subsequent cutting of this work-hardened surface can cause rapid tool failure.

TABLE 11. TURNING TUNGSTEN

Operation	Descaling		Turning		
Workpiece Temp, F	75	75	800	800	
Tool Geometry	A	B, C, D, E		F	G
Type of Cut	Scale removal	Rough	Finish	Finish	Finish
Feed, ipr	0.02-0.04	0.02	0.005- 0.02	*	0.003- 0.006
Speed, fpm	50-60	100- 150	150- 250	15-60	30-40
Depth of Cut, inch	0.125-0.250	1/8-1/4	1/64-1/32	*	0.01- 0.015
Lubrication	Dry	Dry	Dry	Dry	Dry
Application	Sintered tungsten			Wrought shapes	

\*No data.

#### Drilling Operations

General Information. Drilling tungsten is an extremely difficult machining operation and requires equipment with adequate power and rigidity. Some investigators recommend heating the workpiece to 750 F and then drilling with carbide drills. Others have obtained satisfactory results by taking special precautions with more conventional techniques.

Since tungsten usually exhibits poor ductility in the thickness direction, spalling at the exit end of through holes can be troublesome. It can be avoided by backing up the workpiece with soft steel. Sharp drills and positive feeds should be used to avoid localized work hardening below the drill point. Short drills should be used to prevent drill deflection and jigs are recommended to insure adequate rigidity of the setup. To avoid overheating, the hole should not be allowed to fill with chips. It is usually desirable to retract the drill frequently in order to remove chips and to clean the flutes of the drill.

Drills. Heavy-duty drills are normally recommended for drilling tungsten. For maximum rigidity, the flute length of drills should be no longer than required for the desired depth of hole, and for unrestricted chip flow through the flutes. The web should be thinned to reduce end pressure.

Carbide drills used for tungsten include the two-fluted solid-carbide type, carbide-tipped spade drills, and Cold-Point drills. The Cold-Point is a patented drill employing a single oil hole, a carbide point, and a negative rake to break chips into small pieces. These are washed up through the flutes by the coolant. A flood of coolant at the drill point helps to minimize cutting temperatures.

All drills should be checked for the recommended drill geometry before being placed in service. Drills should be resharpened accurately on a drill grinder. The point angle, relief angle, and web thickness should be checked after each resharpening.

The drill should be examined periodically during production. Do not drill or continue to drill with a dull drill, because the hole will work harden, making further drilling virtually impossible. Hence, an arbitrary drill-replacement schedule should be established to minimize work and tool spoilage.

Cobalt high-speed steel, of both the molybdenum and tungsten types, has been used for drilling tungsten. Molybdenum high-speed steels (M-2 or M-3) also have been used at somewhat reduced drill life.

Tungsten can be drilled with carbide drills if proper precautions are taken. A very rigid work-drill-machine setup and excellent machining conditions are necessary. Carbide Grade C-2, the same as that used in turning, should be satisfactory.

Conditions and tool geometries which have been described as being suitable for drilling tungsten are indicated in Tables 12 and 13.

Power feeds possibly can be used later at a feed rate of around 0.001 to 0.0015 ipr for the 1/8 to 1/4-inch drill sizes. In any event, a positive feed should always be maintained. The drill should never ride without cutting since the rubbing action work hardens the base of the hole.

TABLE 12. DRILL MATERIALS AND GEOMETRIES SUGGESTED  
FOR DRILLING TUNGSTEN

Drill Material	Carbide <sup>(a)</sup>			High-speed steel <sup>(b)</sup>
	Solid <sup>(c)</sup>	Tipped <sup>(d)</sup>	Tipped <sup>(e)</sup>	Heavy duty <sup>(f)</sup>
Point Angle, degrees	135	118 or 140	118	118
Helix Angle, degrees	34	0	20	27-32
Relief Angle <sup>(g)</sup> , degrees	14-20	14-20	14-20	14-20
Lip Angle, degrees	--	--	--	-5
Web Thickness at Point	Approximately 1/3 the original web thickness, determine by trial			Form lip angle by thinning web

(a) C-2 type carbide.

(b) T-5, M-3, or M-2 types of high-speed steels have been used.

(c) For small holes up to 1/8-inch diameter.

(d) For shallow holes greater than 1/4-inch diameter.

(e) For deeper holes greater than 1/4-inch diameter.

(f) Similar to "stove burner drills".

(g) Relief angle decreases beyond this range for drills greater  
than 1/4-inch diameter.



TABLE 13. SPEEDS AND FEEDS SUGGESTED FOR  
DRILLING TUNGSTEN

Drill Material	Carbide	High-speed steel
Feed	Steady hand feed (0.0005 ipr)	Heavy hand feed
Speed, fpm	15 to 20	15 to 20
Lubricants	Sulfurized mineral oil, or sulfo- chlorinated mineral oil thinned 1:1 with kerosene. Hot machining, using carbide drills, is done dry.	

### Molybdenum

#### General Information

The machining characteristics of molybdenum have been variously described as being similar to those of cast iron or of 1040 steel heat treated to 30 R<sub>C</sub>. There are, however, certain fundamental differences. Molybdenum workpieces tend to chip or break out during machining. This is especially true of those with coarse, equiaxed structures. Cohesion is low and entire grains can be pulled out of the machined surface. This phenomenon makes it unusually difficult to machine sintered (unworked) or recrystallized molybdenum to a smooth finish. Wrought molybdenum is also difficult to machine, but for a different reason. The strength of the long fibers dulls the cutting edge rapidly and can even break the tool tip.

Molybdenum can produce curled chips or fine, abrasive dust depending on machining conditions. Abrasive dust causes rapid tool breakdown unless removed from the cutting site. Molybdenum also builds up on the cutting edge of the tool--even at high speeds--which is contrary to steel's behavior. The resulting built-up edge sloughs off periodically taking part of the cutting edge with it. This type of chipping can be minimized by employing the proper tool geometry and by flooding the cutting site with appropriate cutting fluids.

Another problem in the machining of molybdenum results from its low coefficient of expansion relative to steel. This problem manifests itself especially during drilling or reaming operations. Here, overheating causes the steel tool to expand and bind in the hole. This problem has been solved by periodic relieving or by delivering the coolant under pressure.

### Effect of Anisotropy, Grain Structure, and Prior Work on Machinability

Highly worked molybdenum is strongly anisotropic, that is, the longitudinal and transverse properties are much higher than those in the thickness direction. Thickness properties approximate those of the unworked metal. Thus, the cutting load resulting from a feed and depth of cut found suitable for the planes of maximum strengths may cause fracture when the load is borne by the weaker plane. In turning, molybdenum tends to chip when running over an edge. In drilling, spalling occurs at the exit end of the hole.

Obviously, altering the grain structure significantly influences the machinability of molybdenum. The optimum structure for best machining properties would be a normally worked molybdenum characterized by uniform fine, fibrous-type grains.

Certain machining techniques are also used to minimize cracking and spalling. In turning, the workpiece can be reversed after partial machining so that the completion of the operation does not produce a terminal face. In drilling, spalling can be alleviated by suitable backing or by drilling the opposite faces of the work.

If the molybdenum workpiece has been highly stressed by prior working, as in forging, stress relieving before machining is recommended. This treatment should avoid cracking or distortion when or if residual stresses are relieved nonuniformly by metal removal. When heavy roughing cuts are taken, stress relieving likewise may be desirable before finish machining. Leave about 0.010 to 0.015 inches for finishing. This eliminates glazing and permits surface finish of 16 microinches to be achieved.

### General Machining Techniques

Since molybdenum has a tendency to chip during machining, precautions should be taken to insure rigid tool-work setups. Adequately powered machine tools free from backlash and vibration should be used. Tools should not be allowed to become dull.

The general machining practices for arc-cast molybdenum and powder-metallurgy molybdenum are about the same. However, the arc-cast variety seems easier to machine since it shows less tendency to crack and spall, and cuts to a better surface finish. Molybdenum alloys seem to machine as readily as the unalloyed varieties with the same structure, except that tools may wear faster due to the increased hardness.

Some machiners use coolants to reduce cutting temperatures and to flush away the highly abrasive powder. Others machine dry since they prefer not to contaminate the chips and thus lower their scrap value. In a large machining program, the scrap value of chips could make a considerable cost difference.

Liquid coolants include cutting oils with additives, kerosene, soluble oil, trichlorethylene, and carbon tetrachloride. Sulfur-base cutting oils have been suggested for roughing cuts. However, they are not recommended for finishing cuts because of their deleterious effects on final properties. Finishing cuts require kerosene, soluble oil in water, trichlorethylene, or carbon tetrachloride. A good coolant which does not contaminate the metal is a 50/50 mixture of chlorinated cutting oil and trichlorethylene.

Cooling a dry cutting operation may be accomplished by an air blast directed at the chip and the cutting edge. When machining is done dry, with or without an air blast, care must be taken to prevent the accumulation of hot chips into small piles in the chip pan. Such piles will trap the heat, hasten oxidation, and thus lower scrap values of the chips. Chips should be scattered uniformly throughout the pan.

### Turning Operations

Much of the information regarding setup, cutting tools, and tool materials described previously for tungsten applies to molybdenum. The work should be firmly chucked, and the tools well supported. The lathe should supply over-all rigidity to the setup. Live centers should be used to prevent galling.

When turning molybdenum, it is usually customary to leave about 0.010 to 0.015 inch for finishing. This eliminates glazing of the surface during the finishing operation.

Table 14 lists some tool geometries and machining conditions which have been used successfully for turning molybdenum and Mo-0.50Ti.

### Milling Operations

Molybdenum and molybdenum alloys can be milled with conventional carbide-tipped face mills designed for cast iron. Side milling and end milling can be accomplished with high-speed steel tools. Table 15 contains some operating data for the above operations.

### Drilling Operations

Drilling molybdenum and molybdenum alloys is best accomplished with high-speed steel drills. Solid carbide drills have been used for holes up to 3/8-inch diameter. Carbide-tipped, straight flute, two-lip drills can be used for larger holes.

Table 16 summarizes the machining conditions used when drilling these materials.

TABLE 14. RECOMMENDATIONS ON TOOL GEOMETRIES AND MACHINING CONDITIONS FOR TURNING MOLYBDENUM AND Mo-0.5Ti

Tool Material:(a)	Molybdenum										Mo-0.5Ti		
	HSS					Carbide					T-5		
	HSS	HSS	C-1	C-2	C-2	C-2	C-2	C-2	C-2	CA	C-1	C-2	C-2
Tool Angles and Radii:(b)													
Back Rake, degrees	10	(d)	0	0	7	0	5 to 10	0	0	0	0	0	0
Side Rake, degrees	5	(d)	20	6	15	20	12	12	18	18	0	20	20
End Relief, degrees	5	(d)	7	6	5	7	10	10	7	7	7	7	7
Side Relief, degrees	5	(d)	7	6	5	7	10	10	7	7	20	7	7
End Cutting Edge, degrees	45	(d)	15	18	15	15	(d)	(d)	--	--	15	15	15
Side Cutting Edge, degrees	30	(d)	15	30	10	15	(d)	(d)	15	15	15	15	15
Nose Radius, inch	.025		.05	18	.60	.05	(d)	(d)	.030	.30	--	.016	--
Type of Cut		Rough	Rough	Rough	Finish	Finish	Rough	Finish					
Speed, fpm(c)	30-50	45-75	175	175-200	25-50	400	100-200	300-600	100	158	375	300-335	300
Feed, ipr	.003	.008-.020	.015-.010	.003-.015	.02-.05	To .010	.006-.008	.006-.008	.0078	.0078	.0078	.009	.009
Depth of Cut, inch	.015-.060	.125-.25	.125-.015	.05-.125	.001-.015	To .015	.125-.0250	.015-.020	.10	.10	.10	.03	.060
Coolant	(d)	(d)	Air blast	(d)	(d)	Air blast	None	None	None	None	None	Soluble oil	Soluble oil (20:1)

(a) HSS = high-speed steel. CA = cast alloy. See Tables A-1 and A-3.

(b) See Figure A-3.

(c) See Table A-4 for conversion of fpm to rpm.

(d) Data not indicated.

TABLE 15. TOOL DESIGN AND OPERATING DATA FOR MILLING  
MOLYBDENUM AND MOLYBDENUM ALLOYS

Workpiece	Molybdenum		Mo-0.5Ti		
Tool Material <sup>(a)</sup>	Carbide	Carbide C-2	HSS M-2	HSS M-2	
Tool Angles, degrees <sup>(b)</sup>					
Axial Rake or Helix	(f)	0	10	30	
Radial Rake	(f)	0	10	7	
Face Relief	(f)	15		5	
Peripheral Relief	(f)	15	6	6	
End Cutting Edge	(f)	10			
Corner	(f)	45			
Milling Cutter	Face Mill		Face Mill	Side <sup>(d)</sup> Mill	End Mill
Type of Cut	Rough	Finish			
Speed, fpm <sup>(c)</sup>	100-150	350-400	225	55	133 <sup>(e)</sup>
Feed, ipt	0.003- 0.005	0.004- 0.005	0.005	0.0038	0.006
Depth of Cut, inch	0.05- 0.10	0.001- 0.003	0.060	0.060	0.10
Coolant			Soluble oil (20:1)	None	None

(a) HSS = high-speed steel. See Tables A-1 and A-3.

(b) See Figure A-1.

(c) See Table A-4 for conversion of fpm to rpm.

(d) 12 teeth staggered.

(e) A speed of 198 fpm can be used with a chemical coolant (15:1).

(f) Same design as for cast iron.

TABLE 16. DRILL DESIGN AND OPERATING DATA FOR DRILLING  
MOLYBDENUM AND MOLYBDENUM ALLOYS

Workpiece	Molybdenum		Mo-0.5Ti	
Tool Material <sup>(a)</sup>	HSS	Carbide	M33 HSS	Carbide C-2
Drill Angles <sup>(b)</sup> , degrees				
Point Angle	Not Available	Not Available	118	118
Clearance Angle	Ditto	Ditto	10	7
Type Point	"	"	Split	Plain
Speed, fpm <sup>(c)</sup>	25-50	40-75	65	100
Feed, ipr	0.003- 0.005	0.003- 0.005	0.006	0.005
Coolant	Sulfur base or highly chlorinated oils		Kerosene and oil	Highly chlorin- ated oil

(a) HSS = High-speed steel. See Tables A-1 and A-3.

(b) See Figure A-2.

(c) See Table A-4 for conversion of fpm to rpm.

## Tantalum and Columbium

### General Information

Tantalum and columbium can be machined without much difficulty, provided their tendency to gall and tear is recognized and overcome by proper techniques. Since roughing cuts followed by light finishing cuts do not result in a satisfactory finish, it is usually best to complete the machining operation with one cut. Galling tendencies are reduced by the proper use of suitable cutting fluids. Even when filing or using emery cloth, the file or cloth should be kept wetted with these fluids.

### Turning Operations

High-speed steel tools seem to be the most suitable for machining tantalum and columbium. Cemented carbide and cast alloy cutting tools may not be satisfactory because of a greater tendency to weld to tantalum and columbium.

Tools should be ground with as much positive rake as the strength of the tool will withstand. Tools with angles similar to those used for annealed copper are satisfactory.

Turning operations have been accomplished satisfactorily using the data found in Table 17.

### Milling Operations

High-speed steel tools are used to mill tantalum and columbium. These tools should have generous clearance, back, and side relief angles. The tabulation shown below contains some data applicable for these tools.

Feed, ipt	0.005
Speed, fpm	100 to 300
Depth of Cut	Same as turning
Cutting Fluid	Same as turning

TABLE 17. TOOL DESIGN AND OPERATING DATA FOR TURNING  
TANTALUM AND COLUMBIUM

Workpiece	Tantalum	Columbium	
Tool Material	HSS	HSS	
Tool Angles and Radii			
Back rake angle, degrees	10 to 20	10	
Side rake angle, degrees	20 to 30	5	
End relief angle, degrees	10 to 15	5	
Side relief angle, degrees	10 to 20	5	
End cutting edge angle, degrees	8 to 15	45	
Side cutting edge angle, degrees	15	30	
Nose radius, inch	1/16 to 1/8	0.020	
Type of Cut	Finish	Rough	Finish
Feed <sup>(a)</sup> , ipr	0.005	0.008-0.012	0.005
Speed <sup>(b)</sup> , fpm	100 to 300	50-60	50-60
Depth <sup>(c)</sup> of Cut, inch	(See below)	0.015-0.060	0.015-0.060
Cutting Fluid <sup>(d)</sup>	Carbon tetra-chloride, light oil trichlor-ethane		

- (a) Feeds must be fast enough to keep the tool tip buried in the work.
- (b) A minimum surface speed of 100 fpm should be used. Slower speeds can cause tearing, especially if annealed metal is being cut.
- (c) It is better to use sharp tools and light feeds and finish machine the work in one cut rather than taking the usual roughing and finishing cuts.
- (d) The use of carbon tetrachloride or a light oil will minimize galling and tearing. Trichlorethane also can be used. The fluid should be flood applied. Since carbon tetrachloride is toxic, a suitable exhaust system should be used near the site of cutting. Insure a good supply of lubricant at the tool point.

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## APPENDIX

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## APPENDIX

TABLE A-1. COMPOSITIONS OF HIGH-SPEED STEELS(a,b)

AISI Code <sup>(c)</sup>	Tungsten	Chromium	Vanadium	Cobalt	Molybdenum
T1	18	4	1		
T4	18	4	1	5	
T5	18-1/2	4	1-3/4	8	
T6	20	4	2	12	
T8	14	4	2	5	
T15	14	4	5	5	
M1	1-1/2	4	1		8
M2	6	4	2		5
M10		4	2		8
M3	6	4	2.75		5
M4	5.50	4	4		4.50
M6	4	4	1.5	12	5
M30	2	4	1.25	5	8
M34	2	4	2	8	8
M15	6.5	4	5	5	3.5
M35	6	4	2	5	5
M36	6	4	2	8	5

(a) Table taken from ASM Metals Handbook, 1954 Supplement, p 22.

(b) For commercial listings, reference can be made to "A Guide to Tool Steels and Carbides", Steel (April 21, 1958).

(c) T1, M1, and M10 perform similarly for ordinary applications. When greater than average red hardness is needed, cobalt-containing grades are recommended. All grades in the molybdenum and tungsten groups are not necessarily comparable. Special-purpose steels such as T6, T8, T15, M6, M35, and M36 seem to have no close counterparts in the other groups. The unique compositions and properties of these steels often suit them to certain applications without competition.

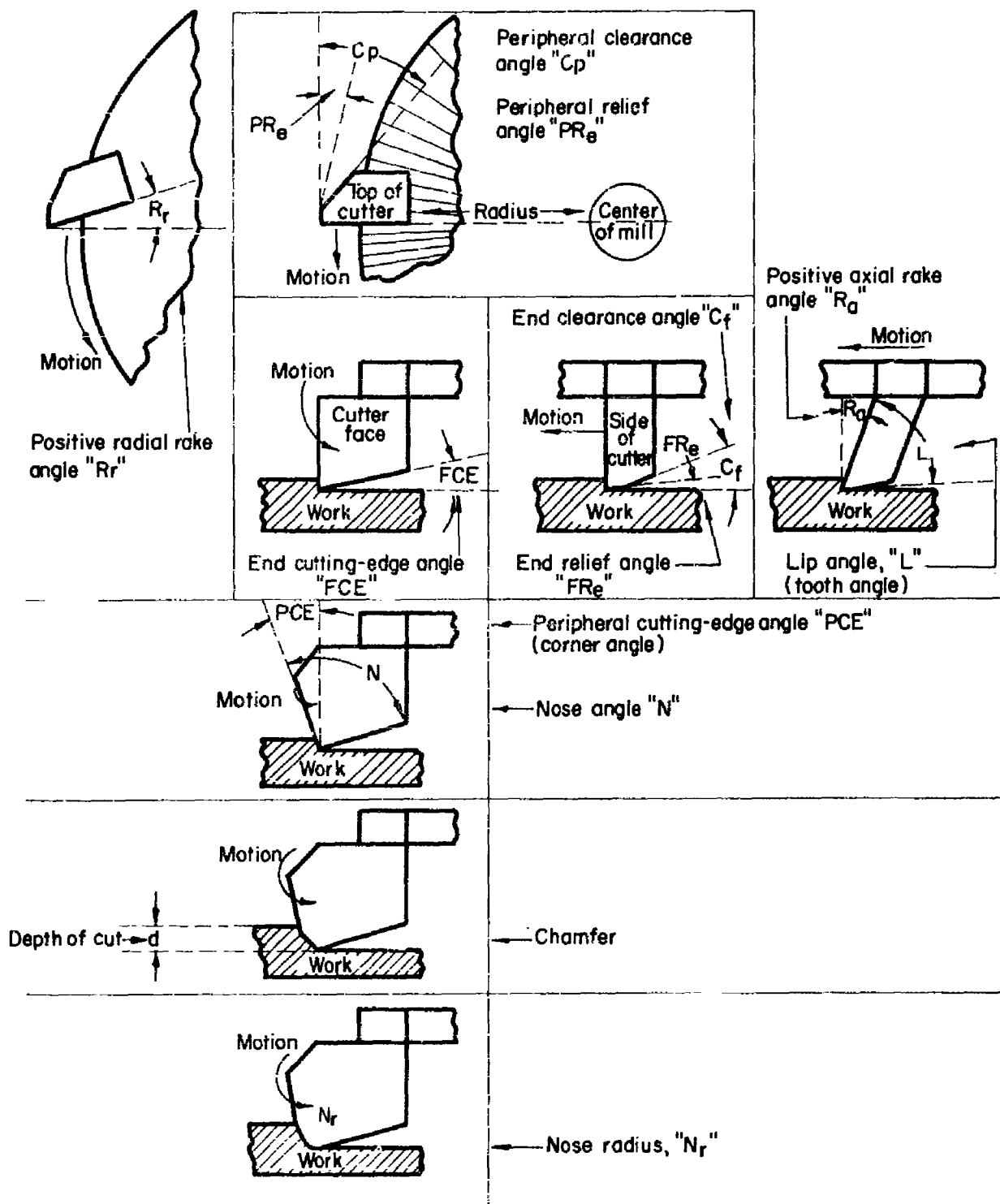
TABLE A-2. EXPLANATION OF GENERAL CODING SYSTEM  
FOR MECHANICAL TOOL HOLDERS

Company Identification	Shape of Insert	Lead Angle	Rake Angle	Type Cut
(a)	T	B	(b)	R
(a)	R	A	(b)	R
(a)	P	A	(b)	R
(a)	S	B	(b)	R
(a)	L	B	(b)	R

<u>Shape of Insert</u>	<u>Lead Angle</u>	<u>Type Cut</u>
T = triangle	A = 0° turning	R = right hand
R = round	B = 15° lead	L = left hand
P = parallelogram	D = 30° lead	N = neutral
S = square	E = 45° lead	
L = rectangle	F = facing	
	G = 0° offset turning	

- (a) Some producers place a letter here for company identification.
- (b) Some companies use the letter "T" for negative rake, "P" for positive rake, and sometimes add "S" to indicate "solid-base" holders.



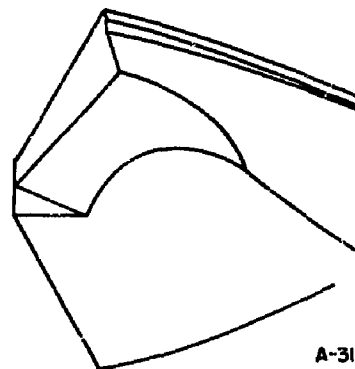
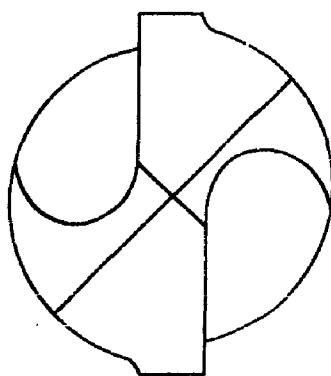
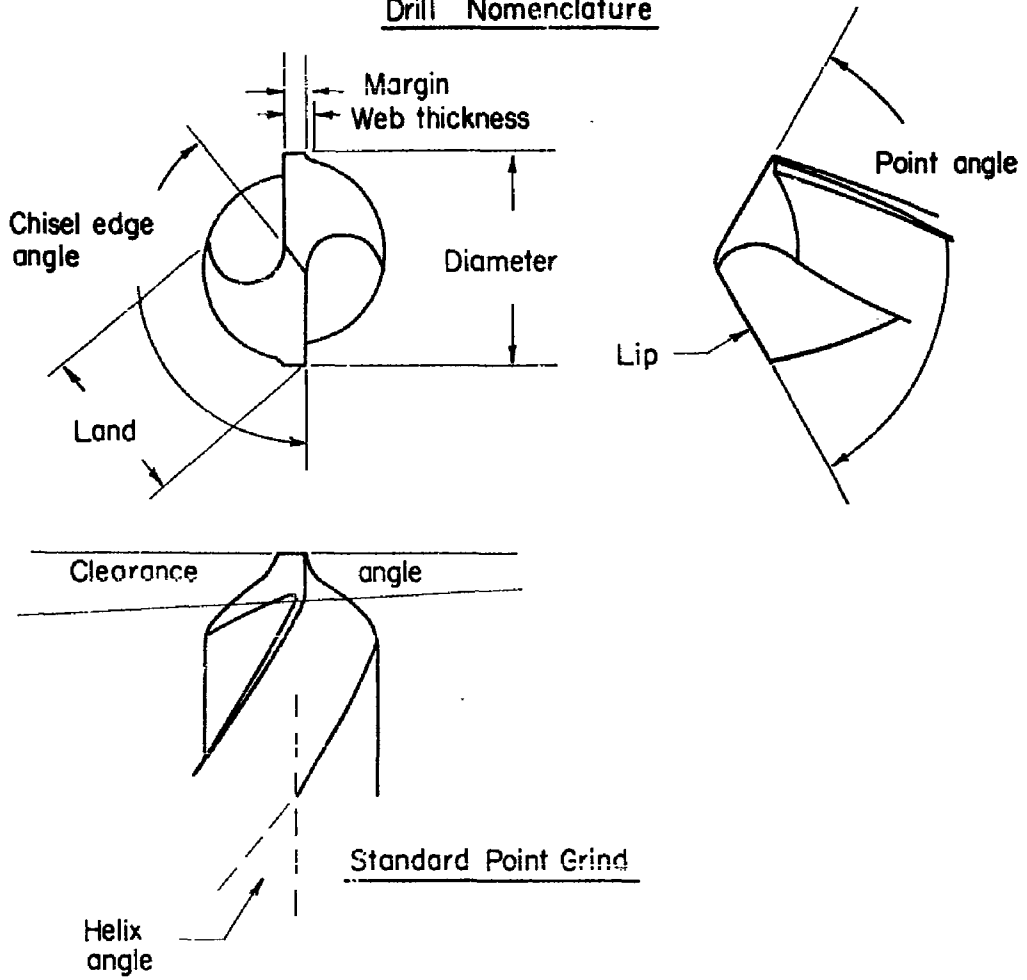


A-24439

FIGURE A-1. NOMENCLATURE FOR FACE MILLING CUTTERS

A-4

# Drill Nomenclature



A-31729

## Crankshaft Point Grind

FIGURE A-2. DRILL NOMENCLATURE AND ILLUSTRATION OF TWO TYPES OF DRILL-POINT GRINDS

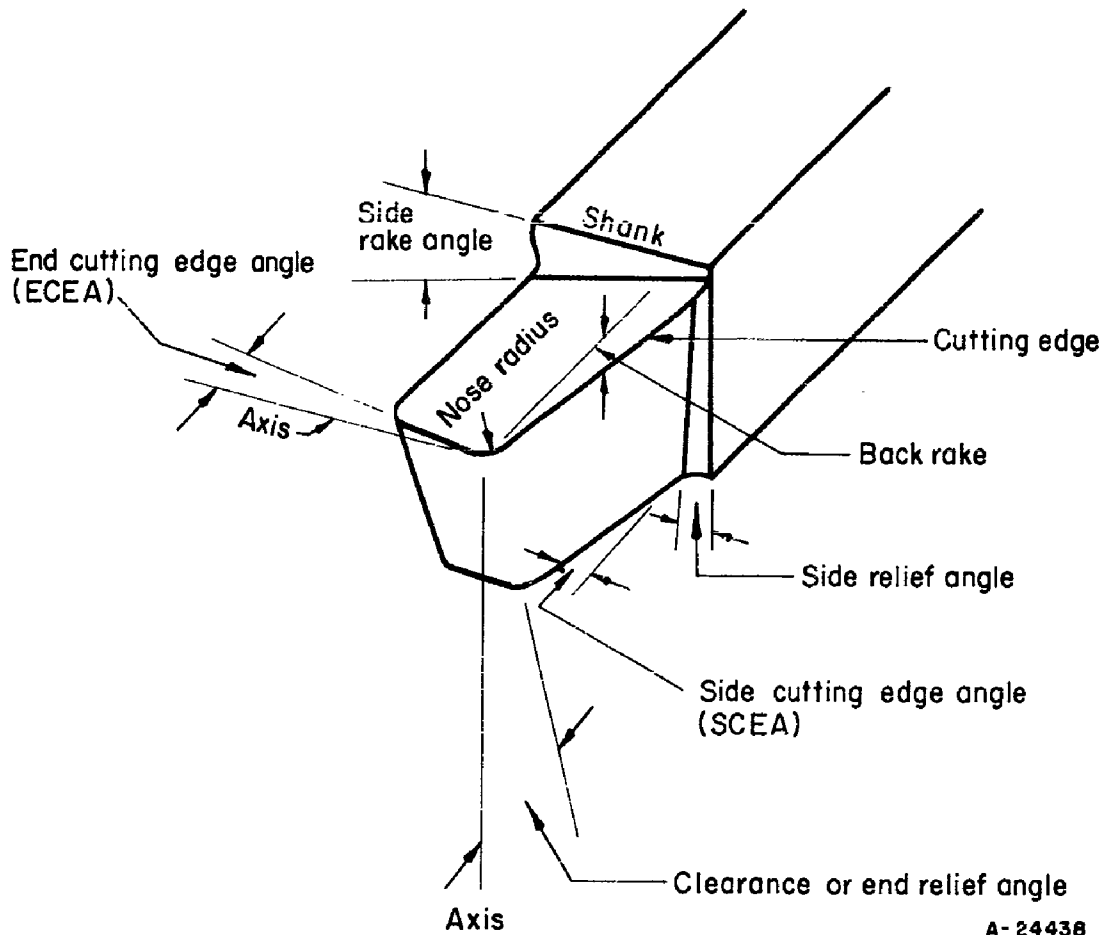


FIGURE A-3. NOMENCLATURE FOR SINGLE-POINT CUTTING TOOLS

TABLE A-3. TOOL MATERIAL GUIDE FOR CARBIDES

CISC Grade	Partial List of Carbides (a) Made by Various Manufacturers												
	Adams	Cornet	Carboloy	Firilmot	Pirnite	Kenna-Metal	Newtomer	Sancvik-Coromant	Talide	Tungsten Alloy	Valenite	Vascoloy-Ranet	Wesson Willey
C-1	C-3	C-4A	883,85C	FA5	H	K1	NC4	n	CB9	9	VC1	2A68,VR54	GS
C-2	C-4	905	905	FA6	HA	K6	NC3	H1	C91	9H	VC2	2A5,VR34	G1
C-3	C-7	999	999	FA7	HE	K8	NC2	H3	C93	9C	VC3	2A7	G4
C-4	C-8	78C	78C	FA8	HF	K11	NC2	H5	C95	9B	VC4	2A7	GF
C-5	C-51	370	370	FI3	TQ4	K21	NS6,NS4	S6,S4	S8X	11T	VC5	EE,VR77	WS
C-6	C-61C	78B	78B	FI4,FI5	TXH,IA	K25	NS3	S1P	S90	9S	VC125	VR77,VR75	26
C-7	C-609	78	78	FI4	IXL	K28	NS2,NS17	S2	S92	10T	VC6	VR75	710
C-7A	C-608	350	350	FI6	IXL,IXL	K3H	NS15	S1	S92X	8T	VC7	E,VR73	WH
C-8	C-605	330	330	FI7	IXL,WF	K4H	NS15	F1	S94	5S	VC8	VR73	WH
						K7H				5S		EH	509,4A

(a) for the same CISC grade, there seem to be no truly equivalent carbides of different brands. Where two carbide grades from the same manufacturer are shown for the same CISC grade, the first is sometimes recommended.

(b) Carbide Industry Standardization Committee.

Notes: (1) The following chip-removal applications have been used for the CISC grade indicated. It will be noted that some grades specify the type of metal removal for which they are best suited.

- C-1 Roughing Cuts - cast iron and nonferrous materials
- C-2 General Purpose - cast iron and nonferrous materials
- C-3 Light Finishing - cast iron and nonferrous materials
- C-4 Precision Boring - cast iron and nonferrous materials
- C-5 Roughing Cuts - steel

- C-5A Roughing Cuts and Heavy Feeds - steel
- C-6 General Purpose - steel
- C-7 Finishing Cuts - heavy feeds - steel
- C-7A Finishing Cuts - fine feeds - steel
- C-8 Precision Boring - steel

(2) This chart can function only as a guide. The so-called "best grade" may differ for each specific job even if the material being machined is the same. The final selection can be made only by trial and error. Instructions regarding the specific use and application of any competitive grade should be obtained directly from the manufacturer.

Diameter in inches	RPM for Given SFPM																			
	10	11	12	13	14	15	16	17	18	19	20	22	25	30	40	50	60	70	80	90
1/16	0.0625	611	917	1222	1528	1833	2139	2445	2750	3056	3361	3667	3973	4278	4584	4889	5195	5500	5806	6112
1/8	0.125	306	458	611	764	917	1070	1222	1375	1528	1681	1833	1986	2139	2292	2445	2597	2750	2903	3056
3/16	0.1875	204	306	407	509	611	713	815	917	1019	1120	1222	1324	1426	1528	1630	1732	1833	1935	2037
1/4	0.25	153	229	306	382	458	534	611	688	764	840	917	993	1070	1146	1222	1299	1375	1451	1528
5/16	0.3125	122	183	244	306	367	428	489	550	611	672	733	794	856	917	978	1039	1100	1161	1222
3/8	0.375	102	153	204	255	306	357	407	458	509	560	611	662	713	764	815	866	917	968	1019
7/16	0.4375	87	131	175	218	262	306	349	393	436	479	523	567	611	655	698	742	786	829	873
1/2	0.5	76	115	153	191	229	267	306	344	382	420	458	497	535	573	611	649	688	726	764
9/16	0.5625	68	102	136	170	204	238	272	306	340	374	408	442	476	510	544	578	612	646	680
5/8	0.625	61	92	122	153	183	213	244	274	304	334	364	394	424	454	484	514	544	574	604
11/16	0.6875	55	83	111	139	167	195	223	251	279	307	335	363	391	419	447	475	503	531	559
3/4	0.75	5	76	102	127	153	178	204	229	255	280	306	331	357	382	407	433	458	484	509
13/16	0.8125	47	71	94	118	141	165	188	212	235	259	282	306	329	353	376	400	423	447	470
7/8	0.875	44	65	87	109	131	153	175	196	218	240	262	284	306	327	349	371	393	415	437
15/16	0.9375	41	61	81	102	122	143	163	183	204	224	244	265	285	306	326	346	367	387	407
1	1.0	38	57	76	96	115	135	153	172	191	210	229	248	267	286	305	324	343	362	381
1-1/8	1.125	34	51	68	85	102	119	136	153	170	187	204	221	238	255	272	289	306	323	340
1-1/4	1.25	31	46	61	76	92	107	122	137	152	167	182	197	212	227	242	257	272	287	302
1-3/8	1.375	28	42	56	69	83	97	111	125	139	153	167	181	195	209	223	237	251	265	279
1-1/2	1.5	25	38	51	64	76	90	102	115	127	140	153	166	178	191	204	216	229	242	255
1-5/8	1.625	24	35	47	59	70	82	94	106	118	129	141	153	165	177	189	201	213	225	237
1-3/4	1.75	22	33	44	55	65	76	87	98	109	119	130	141	152	163	174	185	196	207	218
1-7/8	1.875	20	31	41	51	61	71	81	91	101	111	121	131	141	151	161	171	181	191	201
2	2.0	19	29	38	48	57	67	76	86	95	105	114	124	133	143	152	162	171	181	191
2-1/4	2.25	17	25	34	42	51	60	69	78	87	96	105	114	123	132	141	150	159	168	177
2-1/2	2.5	15	23	31	38	46	54	62	70	78	86	94	102	110	118	126	134	142	150	158
2-3/4	2.75	14	21	28	35	42	50	57	64	71	78	85	92	99	106	113	120	127	134	141
3	3.0	13	19	25	32	38	45	51	58	64	71	77	84	90	97	103	110	116	123	129

TABLE A-4. CONVERSION OF SFPM TO RPM

LIST OF DMIC MEMORANDA ISSUED  
DEFENSE METALS INFORMATION CENTER  
Battelle Memorial Institute  
Columbus 1, Ohio

Copies of the technical memoranda listed below may be obtained from DMIC at no cost by Government agencies and by Government contractors, subcontractors, and their suppliers. Others may obtain copies from the Office of Technical Services, Department of Commerce, Washington 25, D. C.

A list of DMIC Memoranda 1-90 may be obtained from DMIC, or see previously issued memoranda.

DMIC Memorandum Number	Title
91	The Emittance of Titanium and Titanium Alloys, March 17, 1961, (PB 161241 \$0.50)
92	Stress-Rupture Strengths of Selected Alloys, March 23, 1961, (AD 255075 \$0.50)
93	A Review of Recent Developments in Titanium and Titanium Alloy Technology, March 27, 1961, (PB 161243 \$0.50)
94	Review of Recent Developments in the Evaluation of Special Metal Properties, March 28, 1961, (PB 161244 \$0.50)
95	Strengthening Mechanisms in Nickel-Base High-Temperature Alloys, April 4, 1961, (PB 161245 \$0.50)
96	Review of Recent Developments in the Technology of Molybdenum and Molybdenum-Base Alloys, April 7, 1961, (PB 161246 \$0.50)
97	Review of Recent Developments in the Technology of Columbium and Tantalum, April 10, 1961, (PB 161247 \$0.50)
98	Electropolishing and Chemical Polishing of High-Strength, High-Temperature Metals and Alloys, April 12, 1961, (PB 161248 \$0.50)
99	Review of Recent Developments in the Technology of High-Strength Stainless Steels, April 14, 1961, (PB 161249 \$0.50)
100	Review of Current Developments in the Metallurgy of High-Strength Steels, April 20, 1961, (PB 161250 \$0.50)
101	Statistical Analysis of Tensile Properties of Heat-Treated Mo-0.5Ti Sheet, April 24, 1961, (AD 255456 \$0.50)
102	Review of Recent Developments on Oxidation-Resistant Coatings for Refractory Metals, April 26, 1961, (AD 255278 \$0.50)
103	The Emittance of Coated Materials Suitable for Elevated-Temperature Use, May 4, 1961, (AD 256479 \$2.75)
104	Review of Recent Developments in the Technology of Nickel-Base and Cobalt-Base Alloys, May 5, 1961, (AD 255659 \$0.50)
105	Review of Recent Developments in the Metallurgy of Beryllium, May 10, 1961, (AD 256206 \$0.50)
106	Survey of Materials for High-Temperature Bearing and Sliding Applications, May 12, 1961, (AD 257408 \$2.00)
107	A Comparison of the Brittle Behavior of Metallic and Nonmetallic Materials, May 16, 1961, (AD 258042 \$0.50)
108	Review of Recent Developments in the Technology of Tungsten, May 18, 1961, (AD 256633 \$0.50)
109	Review of Recent Developments in Metals Joining, May 25, 1961, (AD 256852 \$0.50)
110	Glass Fiber for Solid-Propellant Rocket-Motor Cases, June 6, 1961
111	The Emittance of Stainless Steels, June 12, 1961
112	Review of Recent Developments in the Evaluation of Special Metal Properties, June 27, 1961
113	A Review of Recent Developments in Titanium and Titanium Alloy Technology, July 3, 1961

B A T T E L L E   M E M O R I A L   I N S T I T U T E

LIST OF DMIC MEMORANDA ISSUED  
(Continued)

DMIC Memorandum Number	Title
114	Review of Recent Developments in the Technology of Molybdenum and Molybdenum-Base Alloys, July 5, 1961
115	Review of Recent Developments in the Technology of Columbium and Tantalum, July 7, 1961
116	General Recommendations on Design Features for Titanium and Zirconium Production-Melting Furnaces, July 19, 1961
117	Review of Recent Developments in the Technology of High-Strength Stainless Steels, July 14, 1961
118	Review of Recent Developments in the Metallurgy of High-Strength Steels, July 21, 1961
119	The Emittance of Iron, Nickel, Cobalt and Their Alloys, July 25, 1961
120	Review of Recent Developments on Oxidation-Resistant Coatings for Refractory Metals, July 31, 1961
121	Fabricating and Machining Practices for the All-Beta Titanium Alloy, August 3, 1961
122	Review of Recent Developments in the Technology of Nickel-Base and Cobalt-Base Alloys, August 4, 1961
123	Review of Recent Developments in the Technology of Beryllium, August 18, 1961
124	Investigation of Delayed-Cracking Phenomenon in Hydrogenated Unalloyed Titanium, August 30, 1961
125	Review of Recent Developments in Metals Joining, September 1, 1961
126	A Review of Recent Developments in Titanium and Titanium Alloy Technology, September 15, 1961
127	Review of Recent Developments in the Technology of Tungsten, September 22, 1961
128	Review of Recent Developments in the Evaluation of Special Metal Properties, September 27, 1961
129	Review of Recent Developments in the Technology of Molybdenum and Molybdenum-Base Alloys, October 6, 1961
130	Review of Recent Developments in the Technology of Columbium and Tantalum, October 10, 1961
131	Review of Recent Developments in the Technology of High-Strength Stainless Steels, October 13, 1961
132	Review of Recent Developments in the Metallurgy of High-Strength Steels, October 20, 1961
133	Titanium in Aerospace Applications, October 24, 1961
134	Machining of Superalloys and Refractory Metals, October 27, 1961